RHIC Electron Cooling Diagnostics

Peter Cameron

eCooling Workshop
26 May 06

Conclusion

- diagnostics for eCooling is pretty much unexplored territory for RHIC Diagnostics team – we have a lot to learn, seek to benefit from those who have actual experience
- We have a very preliminary plan that we think meets a good portion of the needs
- looking for advice regarding what needs to be measured
- looking for advice on how to better utilize existing RHIC diagnostics for eCooling
- looking for good ideas for new diagnostics

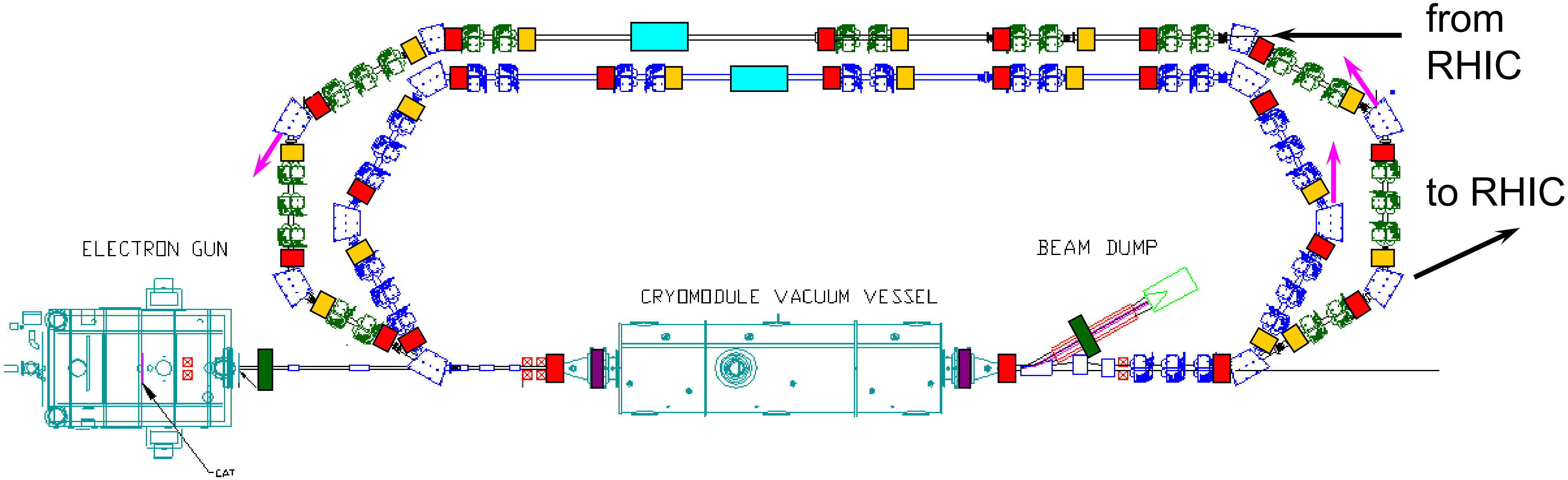
Outline

- **ERL portion of RHIC eCooler**
- The Cooling Section
  - Machine Parameters
  - Devices and Accelerator Physics Requirements
- Diagnostics by system
  - BPMs
  - Velocity match
  - Recombination
  - Schottky/IPM
  - Beam Transfer Function
  - what else?
- Conclusion

ERL Portion of RHIC eCooler

Legend:

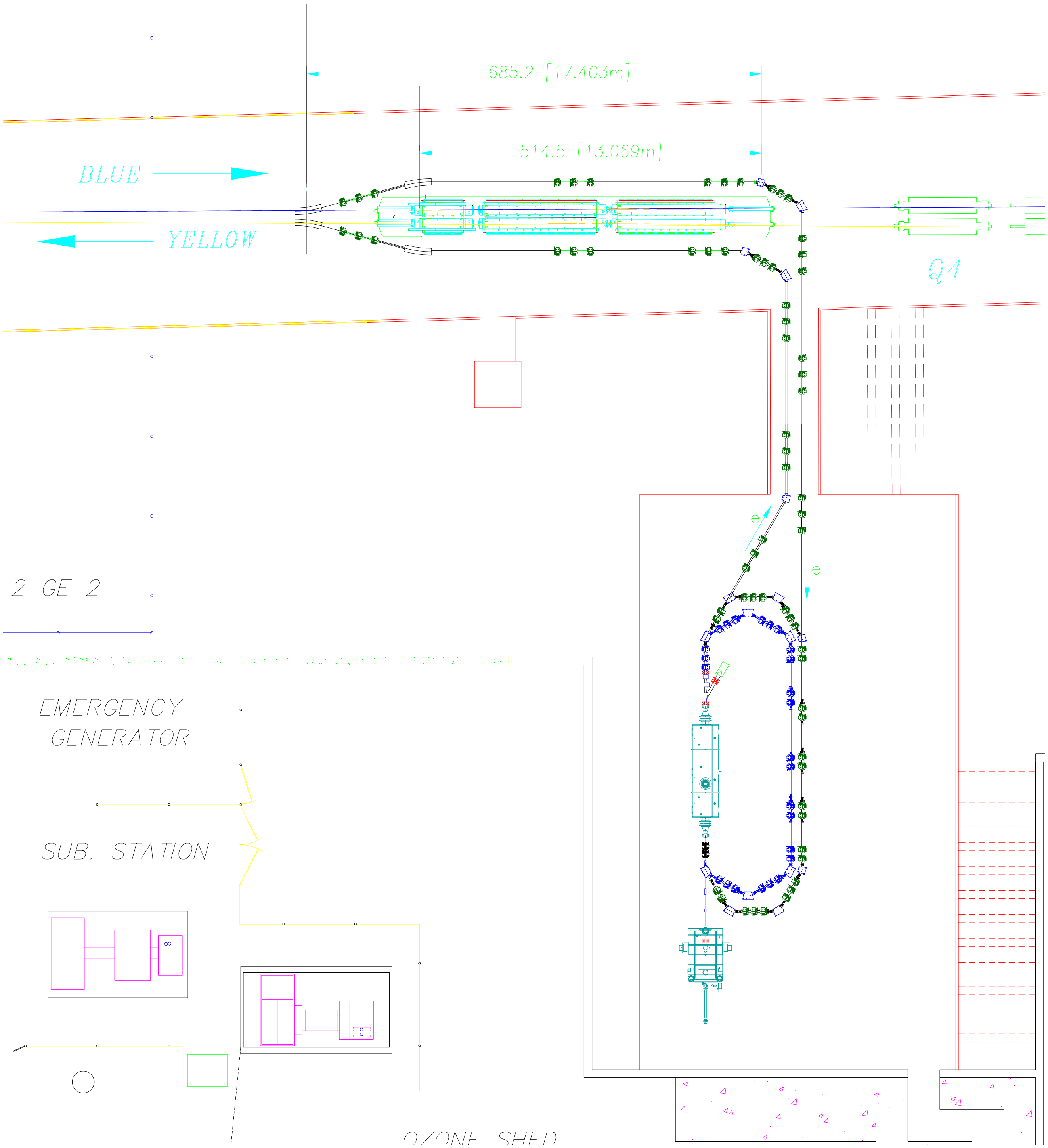
- BPM
- Cross (flag, WS,…)
- Synchrotron light
- DCCT
- HOM probes
- BTF pickup



Outline

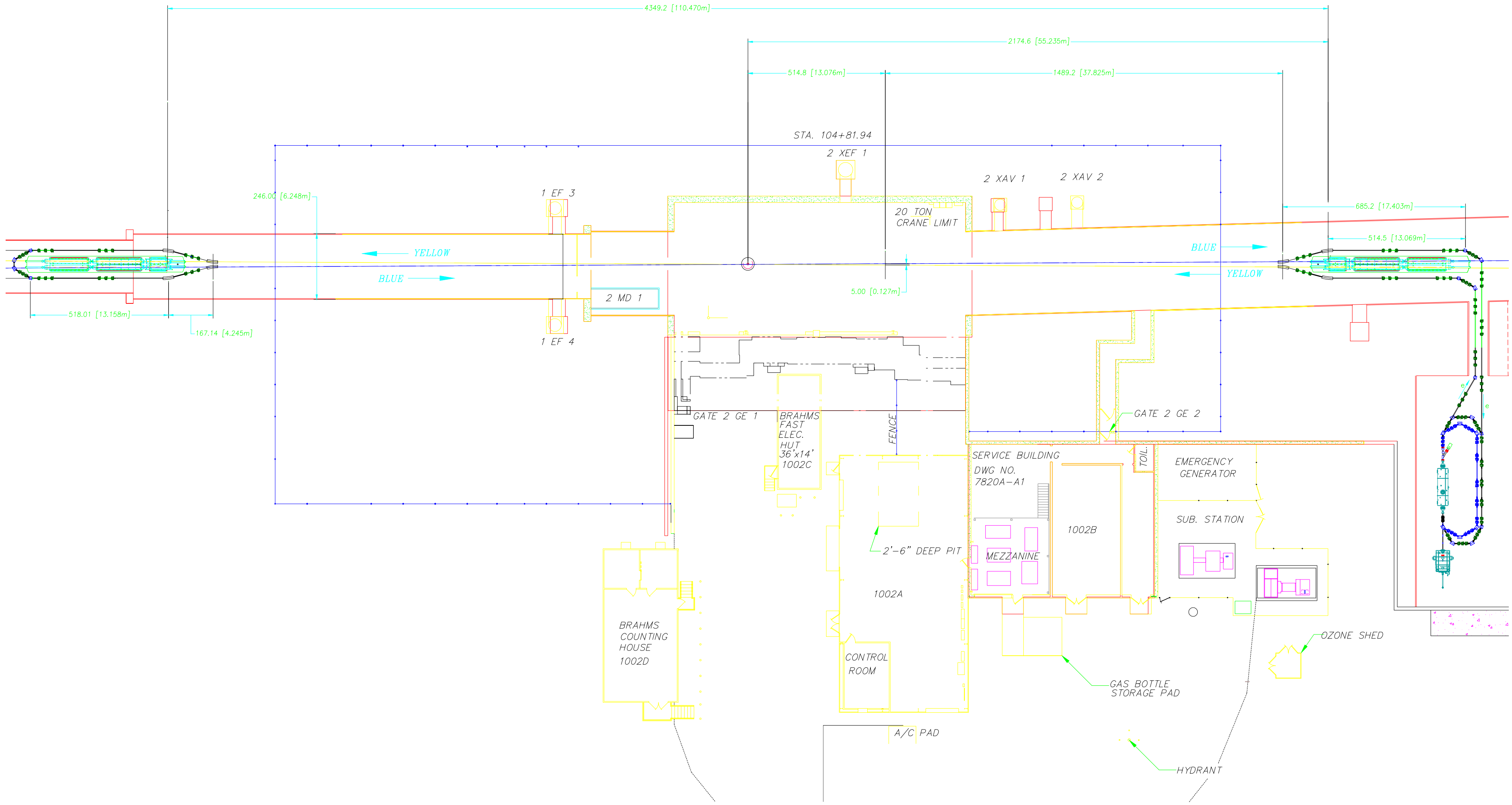
- ERL portion of RHIC eCooler
- **The Cooling Section**
  - **Machine Parameters**
  - **Devices and Accelerator Physics Requirements**
- Diagnostics by system
  - BPMs
  - Velocity match
  - Recombination
  - Schottky/IPM
  - Beam Transfer Function
  - what else?
- Conclusion

E-cooler ERL matched to RHIC

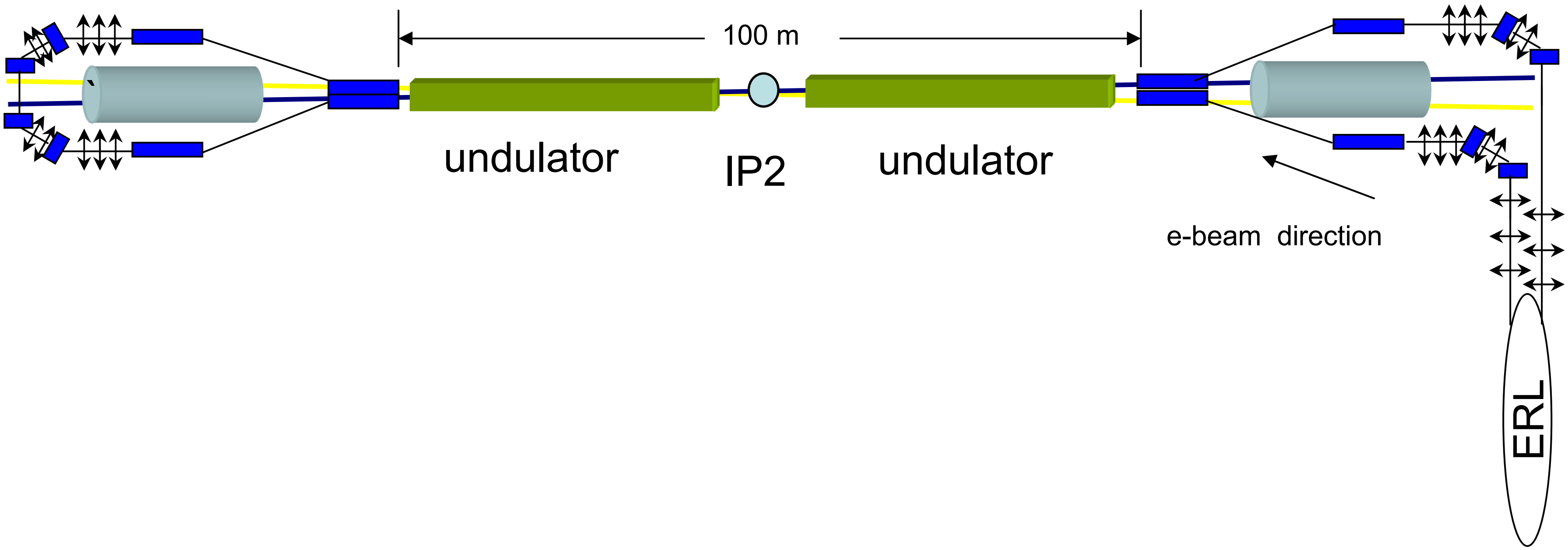


BROOKHAVEN
NATIONAL LABORATORY

IP 2 with ERL e-cooler plan view



IP 2 with ERL e-cooler plan view



A parameter list for the cooler

- Gold ions at 100 GeV/A and protons at 250 GeV
- Ion number per bunch 10^9 gold or $2x10^{11}$ protons
- Ion charge 79 or 1
- Initial normalized rms emittance 2.5 μm (in both transverse planes)
- Initial momentum spread $5 \cdot 10^{-4}$
- Initial rms bunch length 19 cm
- 110 stored bunches
- RF frequency (store) 197.043
- Bunch frequency 9.383 MHz
- ERL RF frequency 703.75 MHz
- Harmonic number 2520
- RF voltage 3 MV
- **Cooling section**
- Wiggler, helical, length 80 meters
- Magnetic field range 0.001 Tesla
- Ions β function in wiggler ≥ 400 m
- **Electron beam**
- Energy 54 MeV Bunch charge 5 nC
- rms bunch length 30 ps rms normalized emittance ≤4 μm
- rms relative momentum spread <0.0005

Cooling-specific Diagnostics Devices and AP Specifications

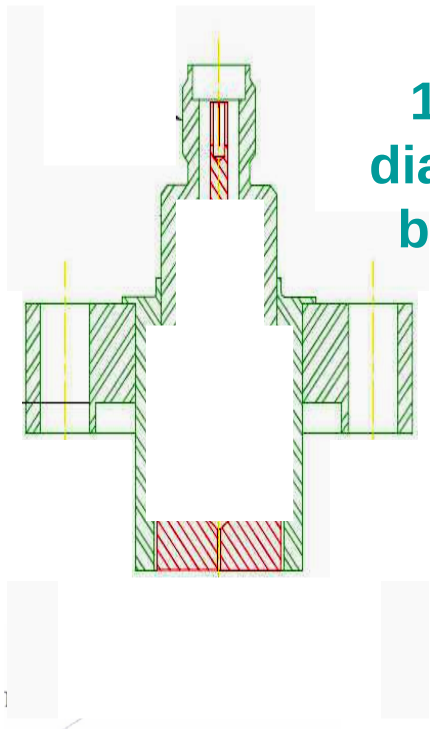
Device	Qty	Range	Accuracy	Resolution	Comments
new					
Relative velocity					
Ion Velocity	2		$2*10^{-3}$	10^{-3}	spectrometer-based
e^- Velocity	2		$2*10^{-3}$	10^{-3}	Compton and spectrometer
Cooling optimization					
Recombination monitor	2	1KHz-1MHz		counting mode	Scraper + PMT, based on 24hr recombination lifetime
Relative Position					
Fast BPMs - ions and e^-	4	½ pipe radius	5μ relative	1μ	WCM-style, simultaneous measurement of ions and e^-
Button BPMs - ions and e^-	160?	½ pipe radius	5μ relative	1μ	With ions and e^- de-phased, located every meter?
Beam Transf Funct	2				Longit and transverse?
existing					
Emittance - ions					
ZDC	4		5%	1%	Requires ion beams in collision
IPM	4		10%	3%	Both planes, both rings
Schottky	12		20%	1%	distribution dependence??? 2GHz, 245MHz, and 1.7GHz TW
Momentum spread					Ions only
WCM	2		5%	1%	Both rings
Schottky	6		10%	1%	2GHz, 245MHz, and 1.7GHz TW

Outline

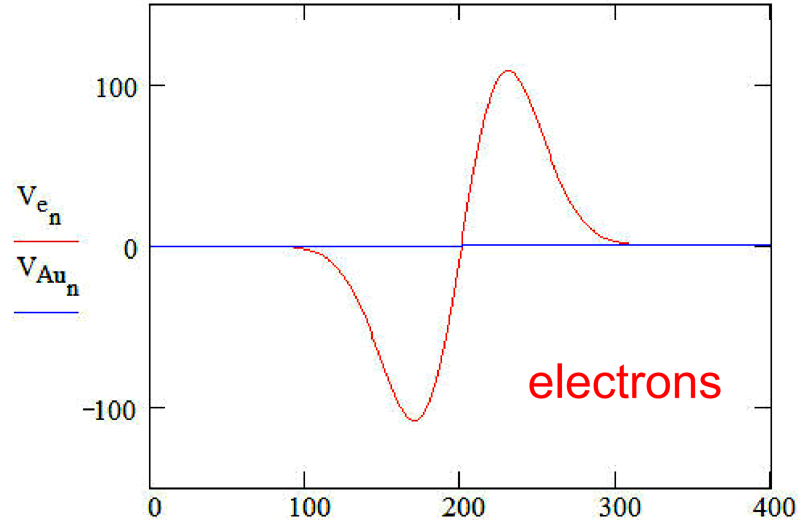
- ERL portion of RHIC eCooler
- The Cooling Section
  - Machine Parameters
  - Devices and Accelerator Physics Requirements
- **Diagnostics by system**
  - **BPMs**
  - **Velocity match**
  - **Recombination**
  - **Schottky/IPM**
  - **Beam Transfer Function**
  - **what else?**
- Conclusion

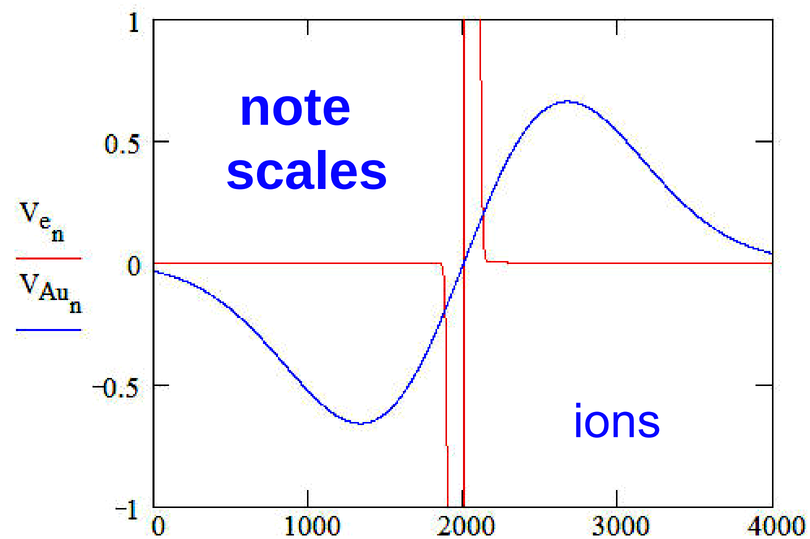
Button Voltages – electrons and ions

Parameter [units]	electrons	ions
bunch charge [nC]	5	15
bunch length [psec]	30	667
3dB point [MHz]	4000	200
Button voltage [V]	110	0.65



10mm diameter button

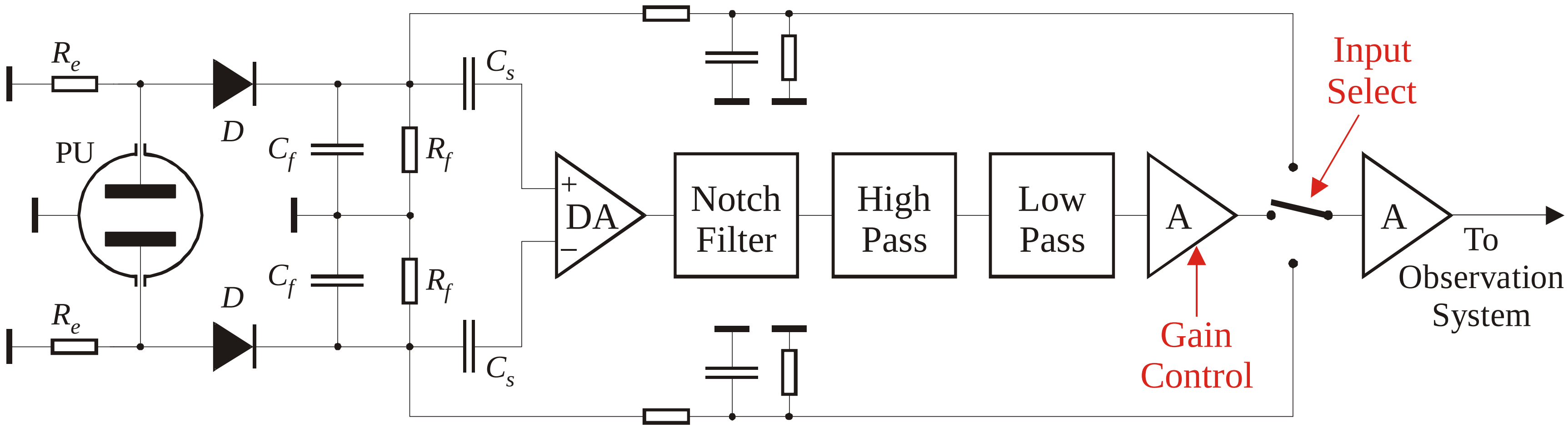




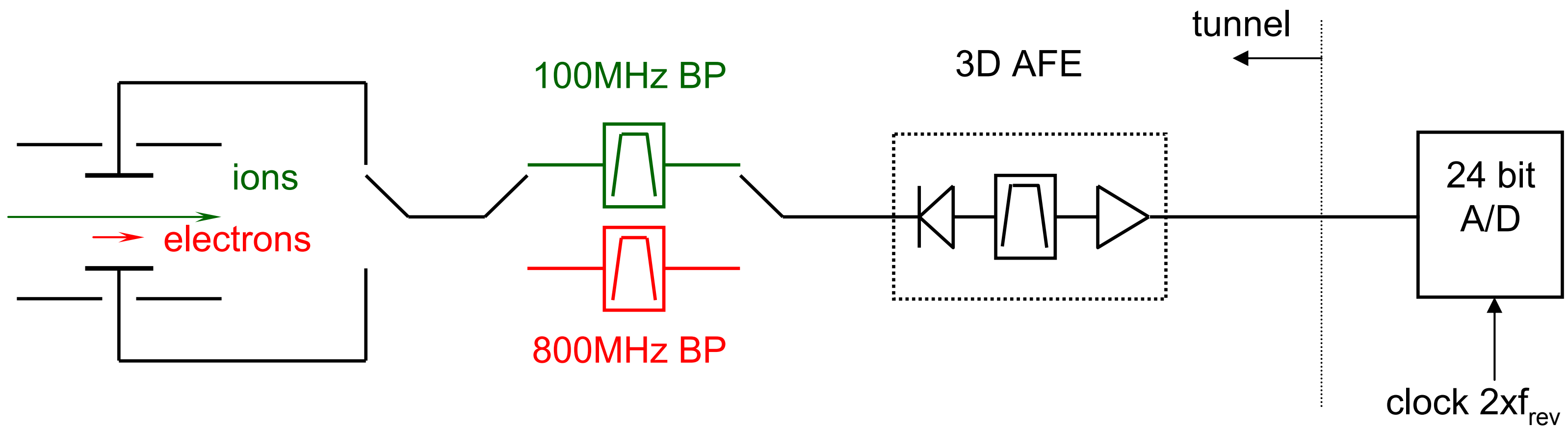
Position measurement

- **Absolute accuracy - not required (save money here)**
- **Relative accuracy**
  - stringent – want to know relative positions of electron and ion beams with good precision (how good is needed?)
  - requires good resolution, matching, stability
  - made difficult by dynamic range - ~50dB difference between ions and electrons
  - made difficult by ~x20 difference in time scales/spectral content between ions and electrons
- **new approach - direct diode detection (3D)**
  - http://doc.cern.ch/archive/electronic/cern/preprints/lhc/lhc-project-report-853.pdf
  - http://dipac2005.web.cern.ch/dipac2005/default.htm
  - <10nm resolution in RHIC when conventional BPM delivers ~1micron
  - switching permits more accurate relative position measurement?

Direct Diode Detection AFE



Position measurement



- Multiplexed BPM (extensive research on switching by Bergoz, though not for this specific application)
- 800MHz BP signal is electrons
- 100MHz BP signal is ~75% ions, 25% electrons
- adjust correctors until the two positions match
- 3D AFE gives best possible sensitivity
- 24 bit digitizer gives dynamic range
- Does not require matched filters
- With clock at 2xf_{rev} can also measure phase if needed (?)

Cooling Diagnostics – fast BPM

- Bandwidth sufficient to look at the electron bunch within the ion bunch
- Broadband BPM – segmented fast Wall Current Monitor
  - Functions as both WCM (sum signal) and BPM (difference signal)
  - Bandwidth limit ~6GHz – marginal for 30ps bunches

CLIC WCM

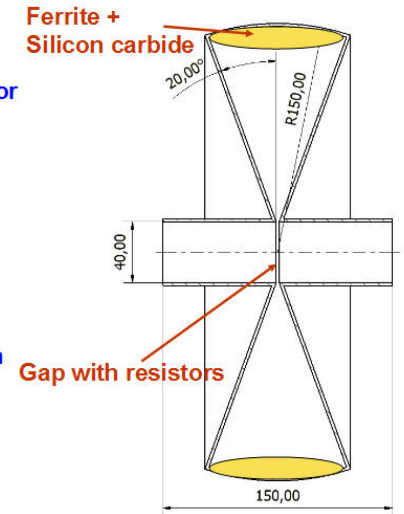
Biconical WCM/BPM
Fritz Caspers

- prototype fabricated and tested at CERN
- 3dB BW ~7GHz without ferrites/absorbers

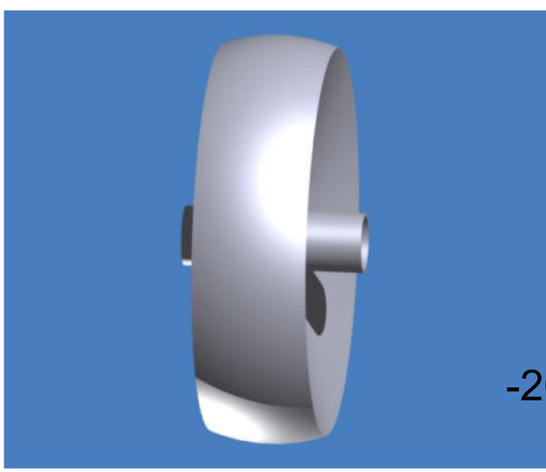
A "biconical" WCM

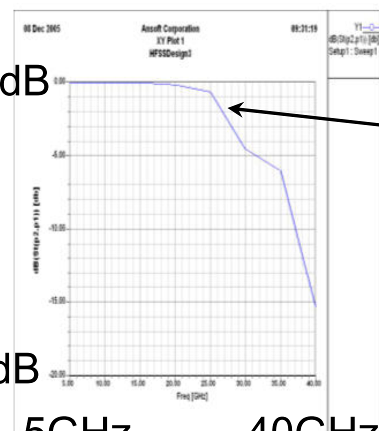
- An idea (Biconical antennas or radial transmission line) by F. Caspers.
- Guides radial spherical TEM wave which is absorbed by Silicon carbide and ferrite.
- No corners to avoid HOM conversions.
- Should have higher bandwidth than traditional tank shapes .
- Optimize angle to gap impedance.

$$Z_{Cone} = \frac{377}{\pi}\ln(\cot\frac{\varphi}{2})$$



"Biconical" WCM



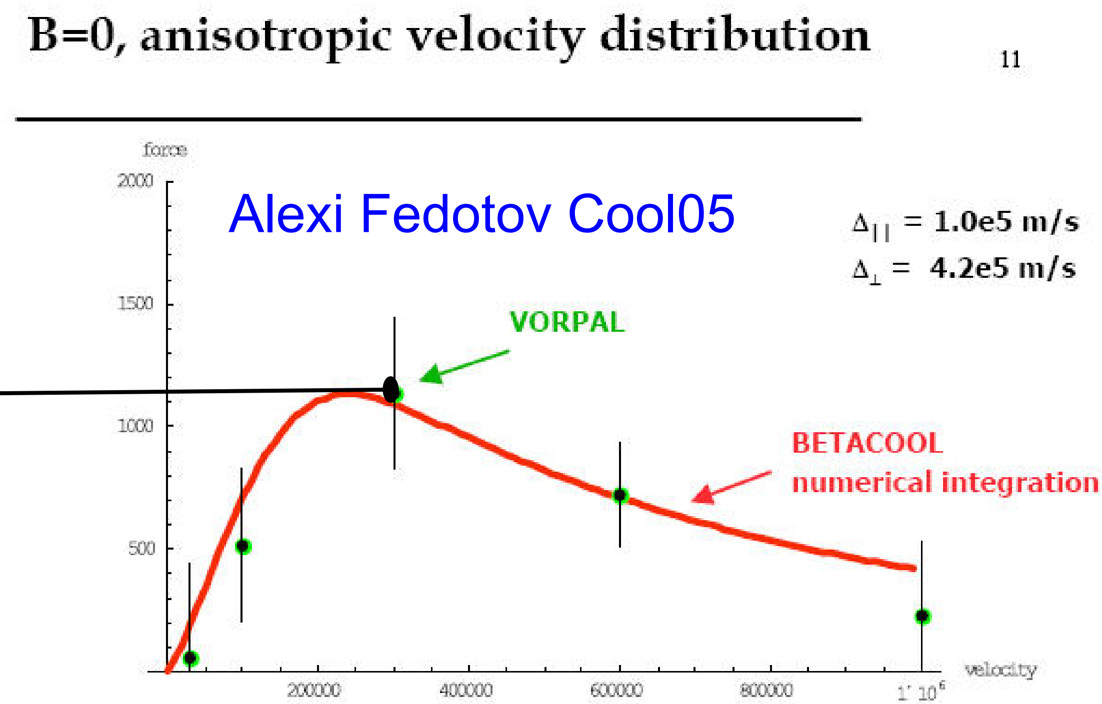


Transmission (S21) simulation of 50ohm setup, but done without absorbing boundary.

- Calculated (HFSS) 3dB point ~25GHz
- Conventional WCM is ~6GHz
- Optical fiber signal path

Cooling Diagnostics – Velocity Match

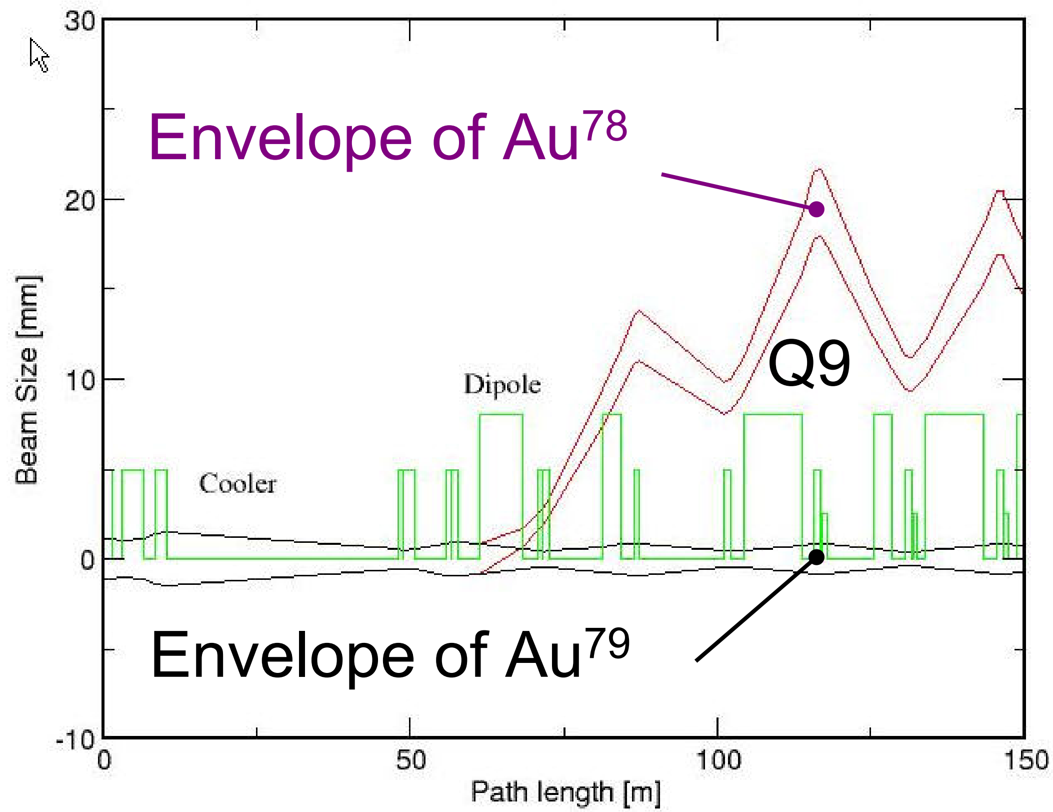
- The idea – get match good enough to permit using recombination monitor for fine tuning
- Assume δv in Ion frame of $3\text{x}10^5$ m/s
- In lab frame this is 30m/s – can't measure
- Energy difference is $(\gamma_e-\gamma_I)/\gamma_e \sim 10^{-3}$



- This can be measured via 'magnetic spectrometer'
  - LEP and SLAC experience ~ 10^{-4} with big effort
  - at RHIC we just need magnet current and transfer function
- e^- beam energy can also be measured by Compton cutoff

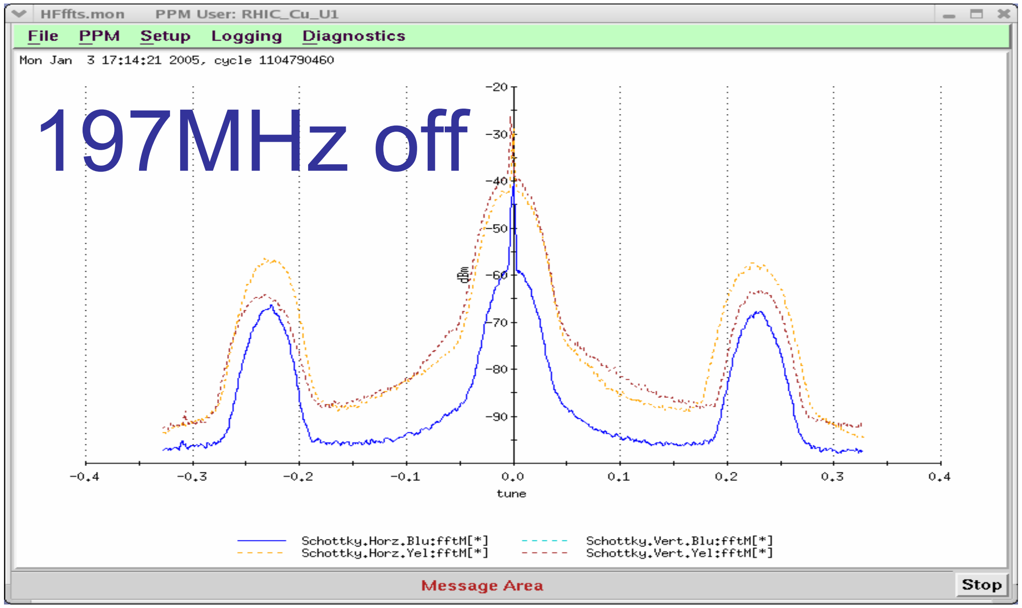
Cooling Diagnostics – Recombination

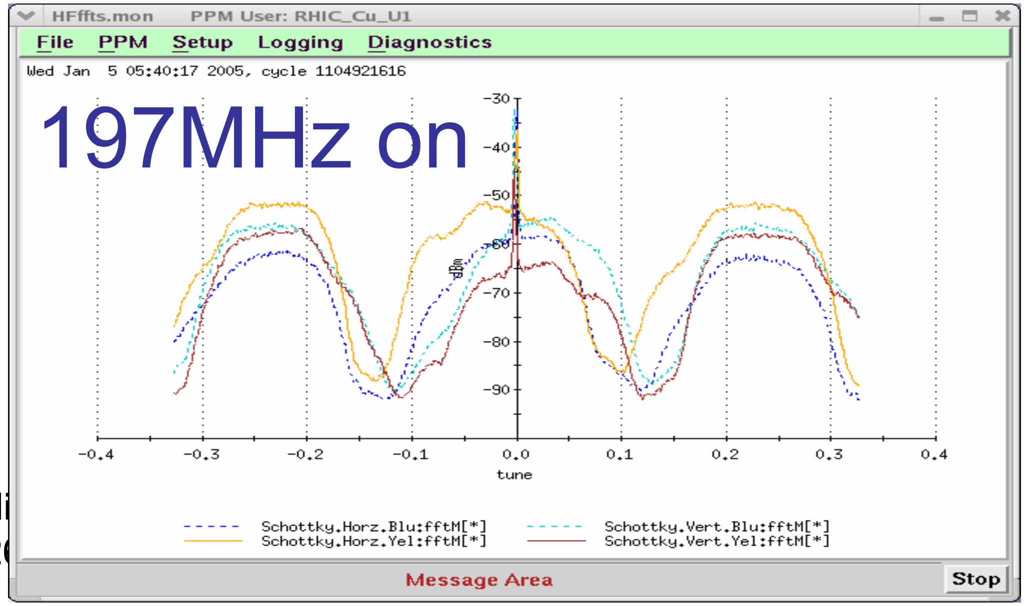
- Use recombination monitor for more sensitive tuning
- With recombination lifetime of 1 day and 10^{11} ions in RHIC, then rate is 1MHz.
- Would like at least tens of Hz to start tuning, limit will be background?
- Scraper plus PMT at Q9 (region of large displacement)



Cooling Diagnostics – Schottky

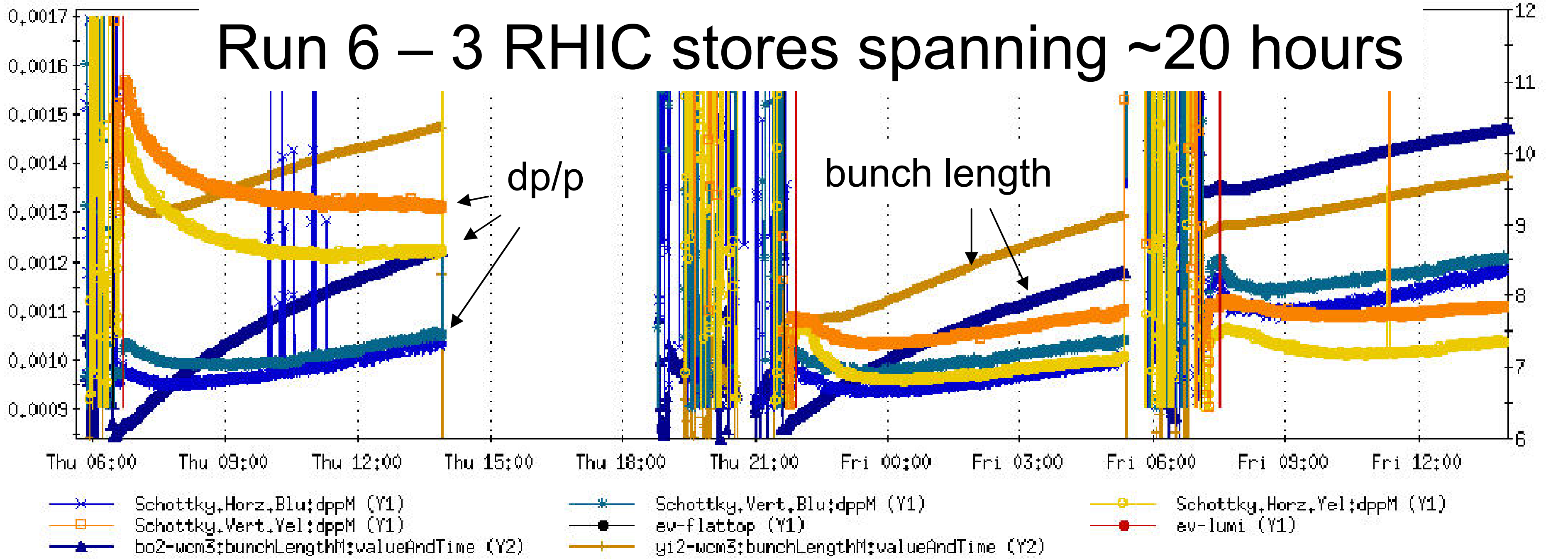
- Three existing systems
  - 2GHz resonant
  - 245MHz resonant
  - 1.7GHz TW
- Can measure emittance and momentum spread with high resolution (Z=79, I=150mA)
- Need refinement of calibration methods
- Need improved understanding of how to properly interpret non-Gaussian profiles

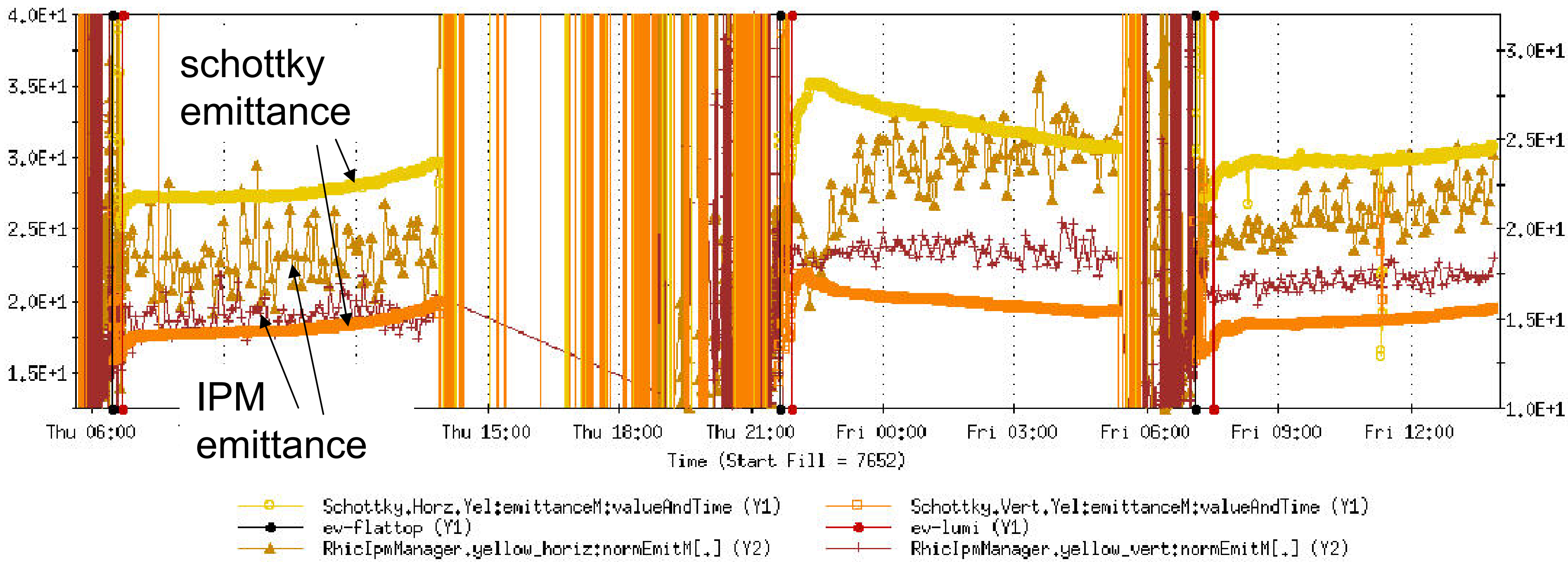




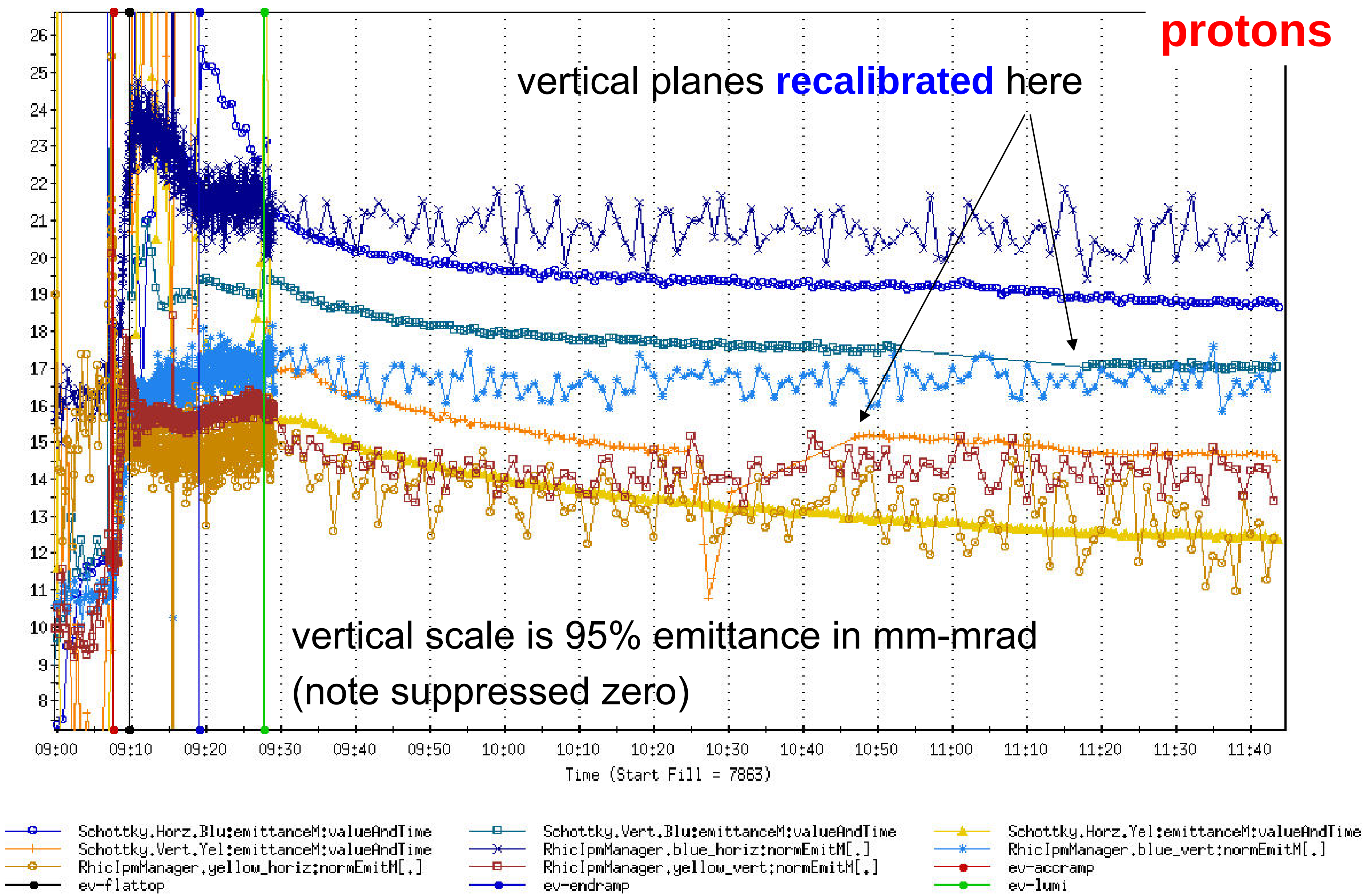
BROOKHAVEN NATIONAL LABORATORY

Run 6 – 3 RHIC stores spanning ~20 hours





RHIC Schottky and IPM emittances

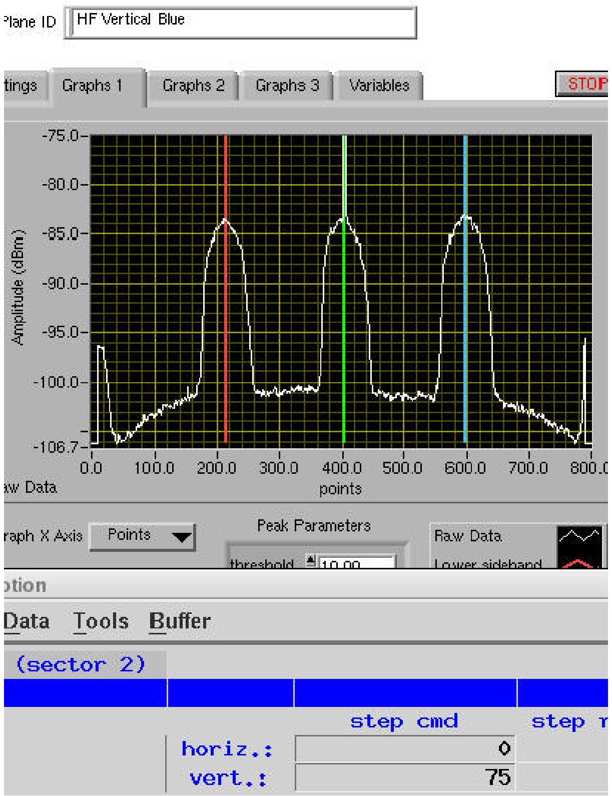


Emittance calibration - the principle

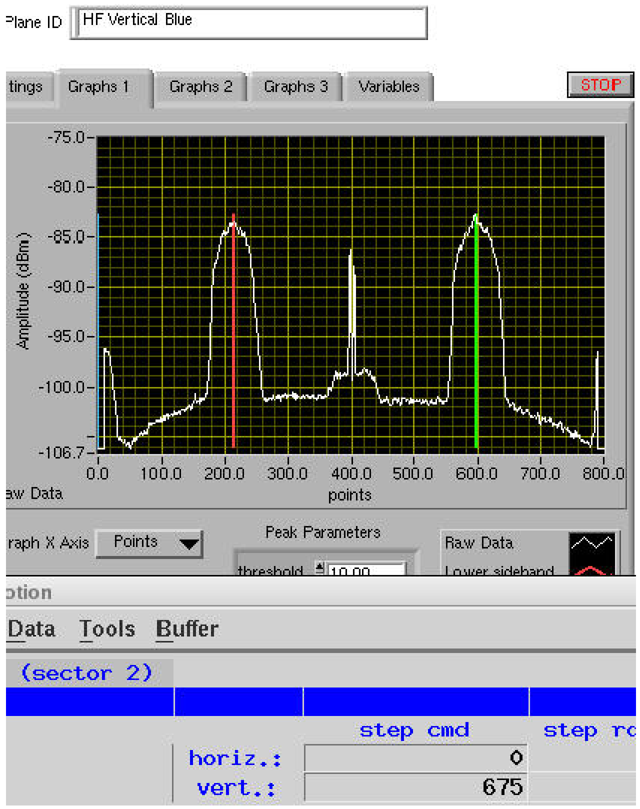
- Simple
- Schottky pickup is moveable $\longrightarrow$ controllable beam offset
- Schottky signal is macro-particle of charge sqrt(N), where N is number of beam particles
- This macro-particle deposits power in the spectrum at both revolution and betatron frequencies
- Beam offset at which power in rev line equals power in betatron lines is the rms beam sigma (see next slide)

Spectra at 3 pickup positions

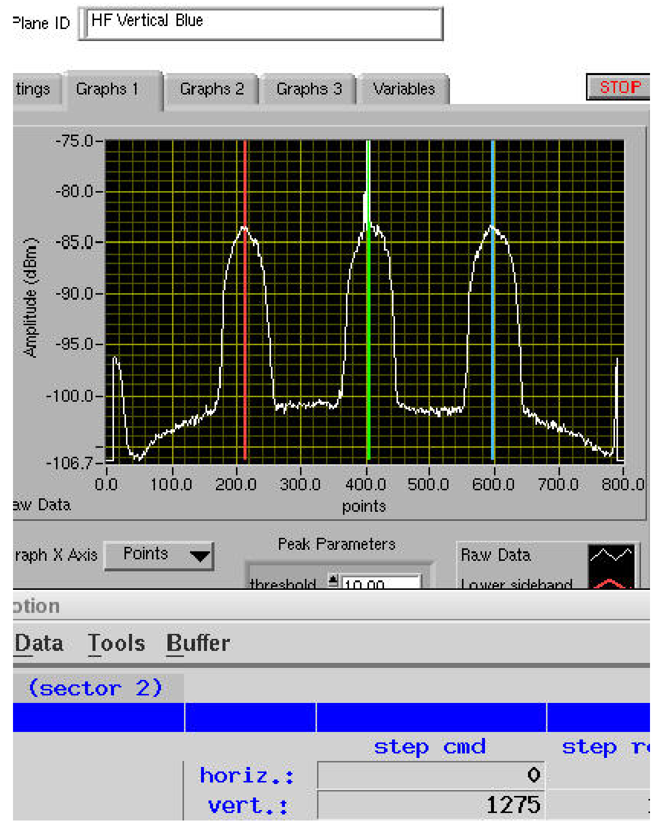
protons



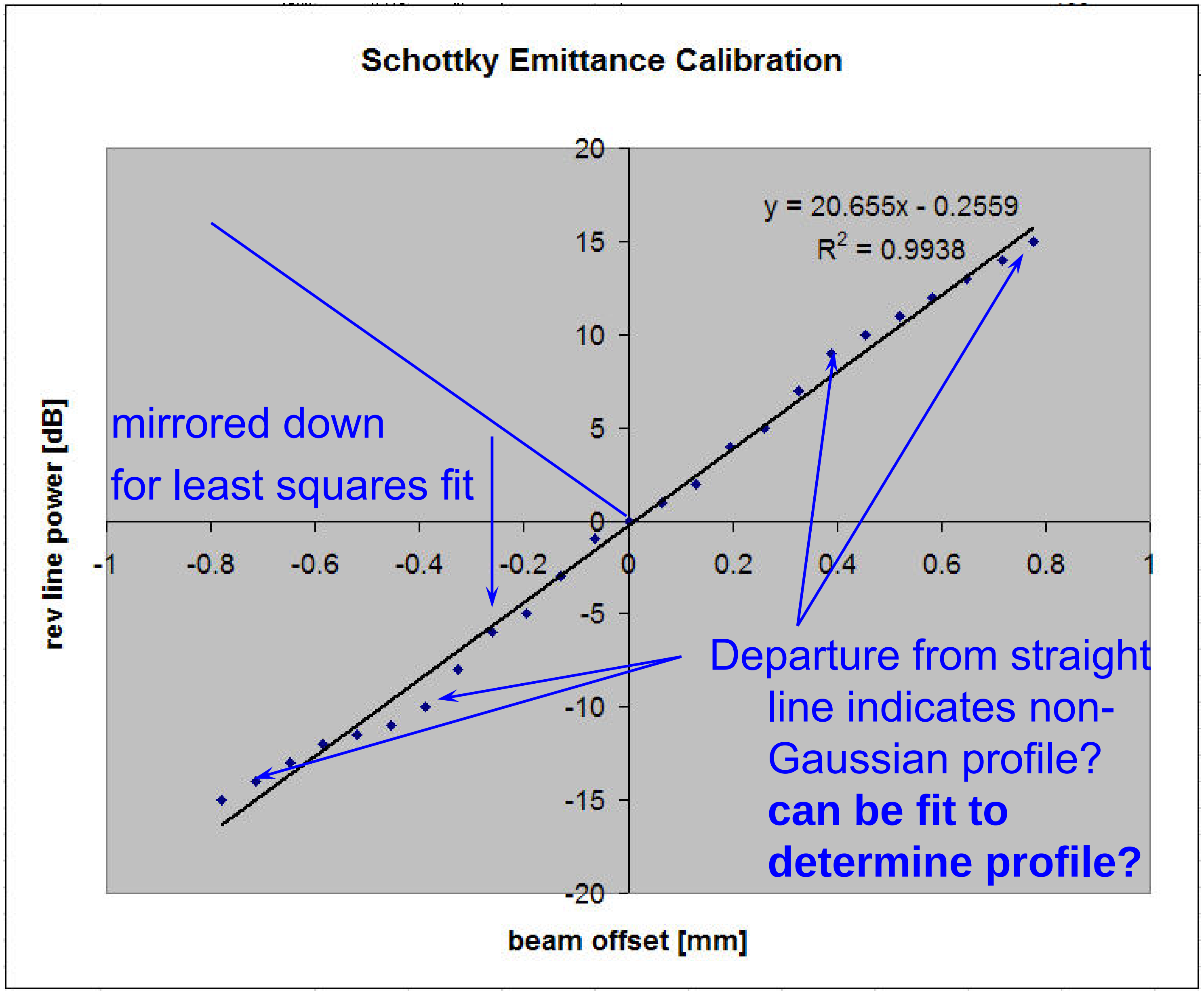
Counts = 75



Counts = 675

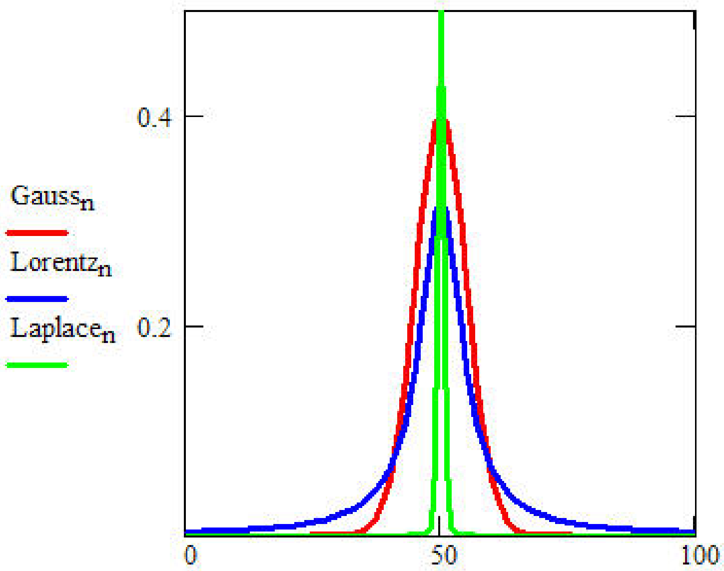


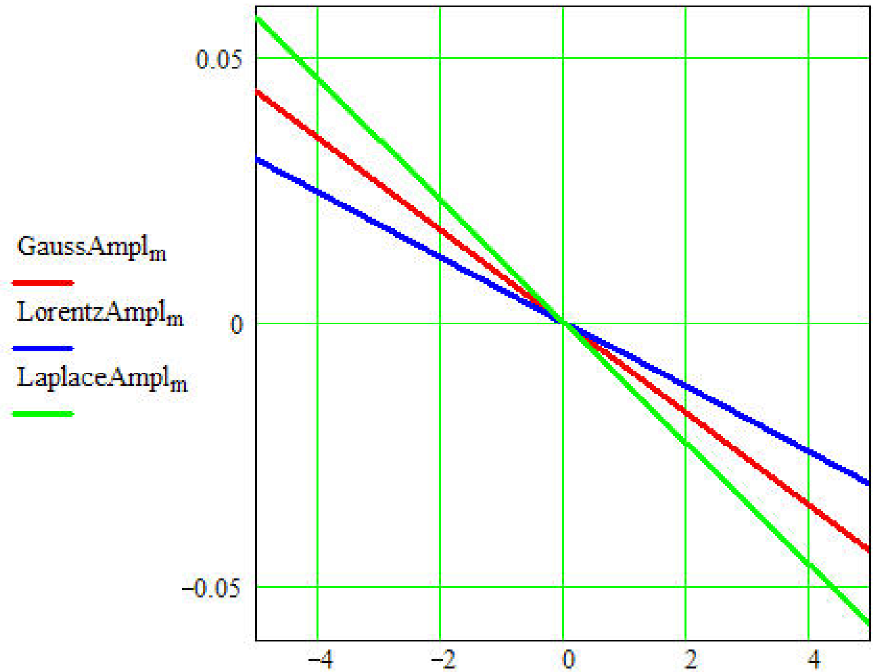
Counts = 1275



Schottky Emittance Calibration
y = 20.655x - 0.2559
R2 = 0.9938
mirrored down
for least squares fit
Departure from straight line indicates non-Gaussian profile?
can be fit to determine profile?
rev line power [dB]
beam offset [mm]
20
15
10
5
0
-5
-10
-15
-20
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Calculated profile dependence of Emittance





pickup offset

can be used to monitor profile evolution, for instance during beam cooling?

What can be measured with Schottky?

- The usual – tune, chrom, emittance,dp/p,…
- Moveable pickup
  - absolute emittance calibration
  - information on transverse profile?
- Lineshape analysis
  - higher order chromaticity
  - non-linear tune spread
  - detailed momentum distribution information
- envelope oscillations

What else?

- antennas for CSR microwave instability
  - needed? where? what frequency?
- what else?

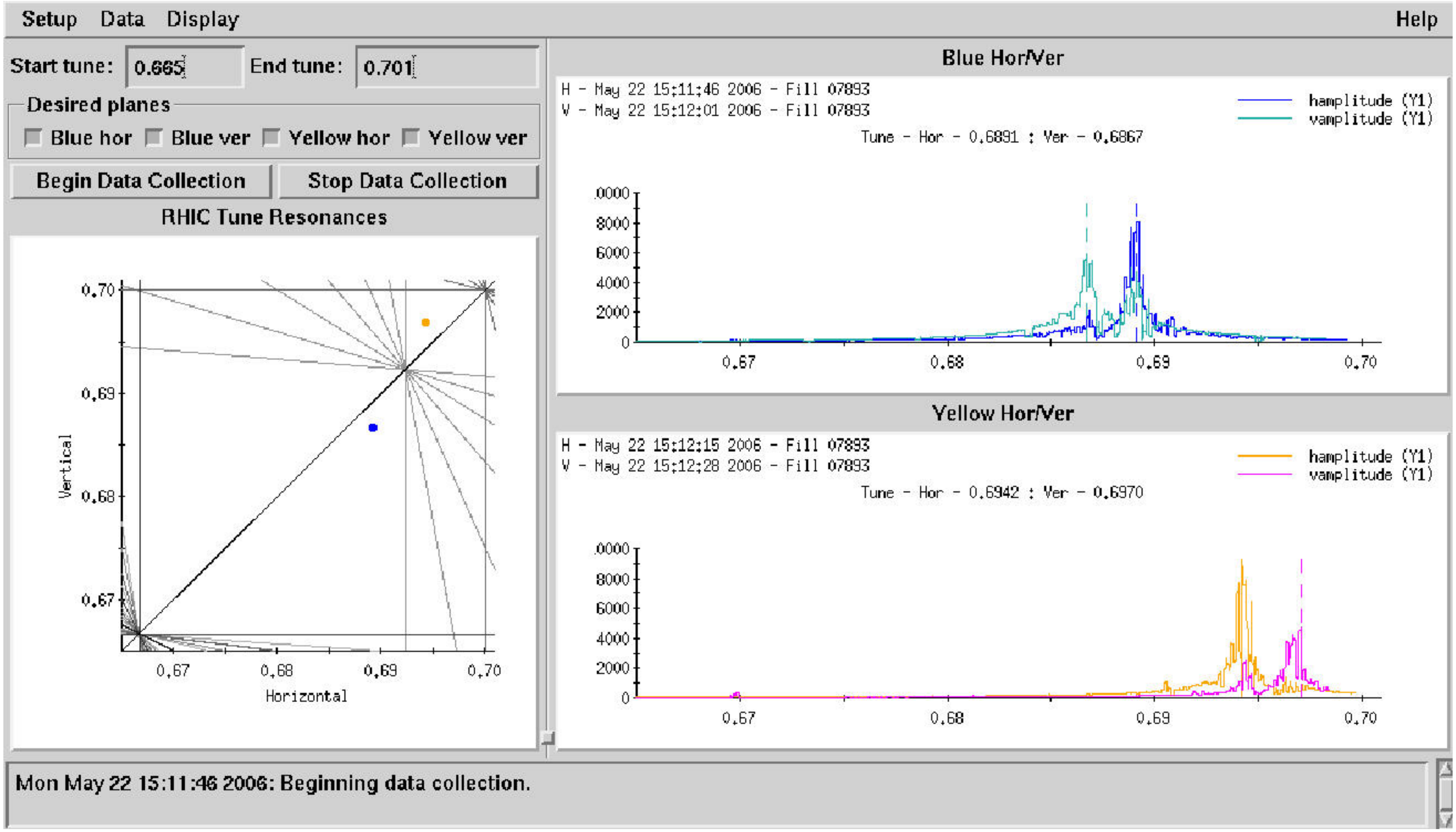
Outline

- ERL portion of RHIC eCooler
- The Cooling Section
  - Machine Parameters
  - Devices and Accelerator Physics Requirements
- **Diagnostics by system**
  - **BPMs**
  - **Velocity match**
  - **Recombination**
  - **Schottky/IPM**
  - **Beam Transfer Function**
  - **what else?**
- Conclusion

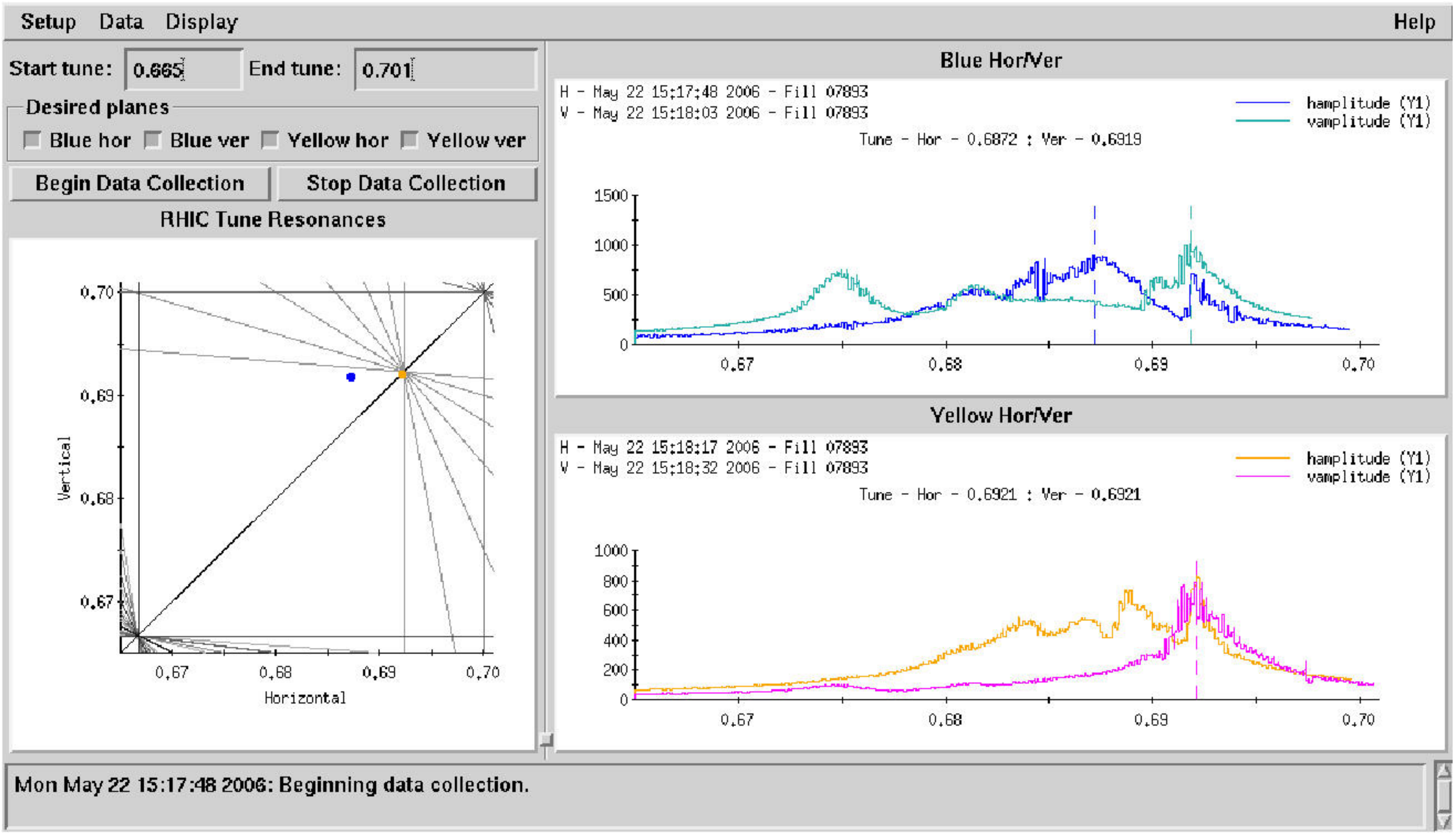
Beam-beam transfer function

- Presently a useful tool in RHIC
  - BTFs, BBTFs, coupling TFs, BB coupling TFs
- How much can be learned with a similar tool during eCooling?
- Relative merits of longitudinal and transverse?

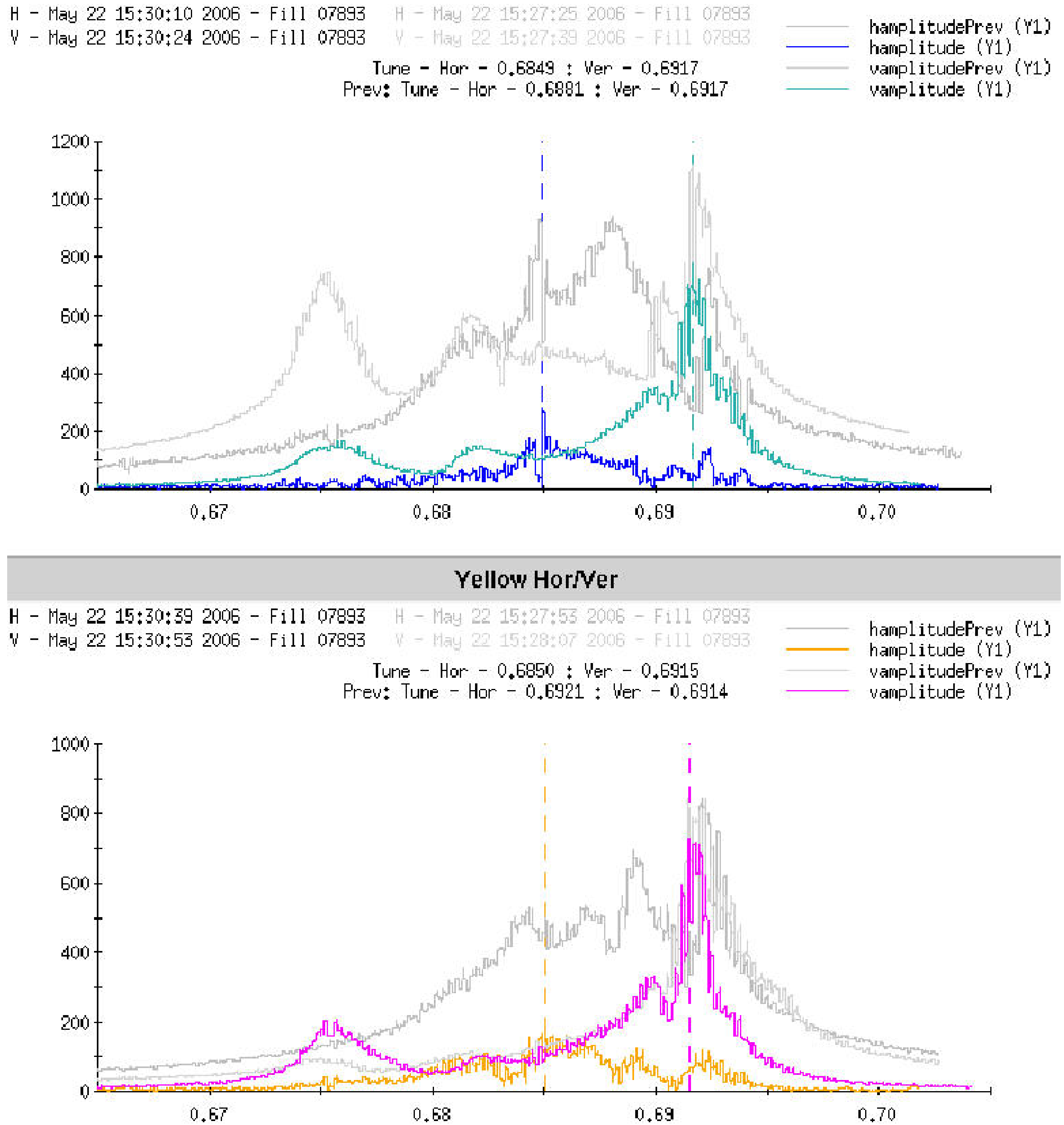
BTF in RHIC before collisions



BTF in RHIC during collisions



BBTF in RHIC during collisions



BROOKHAVEN NATIONAL LABORATORY

Beam-beam transfer function for eCooling

- Presently a useful tool in RHIC
  - BTFs, BBTFs, coupling TFs, BB coupling TFs
- How much can be learned (ie friction force?) with a similar tool during eCooling?
- Transverse BTF
  - for transverse, excite electron beam in vicinity of ion beam betatron frequency? gives enhancement (and uncertainty)
  - 1μ ion beam excitation gives ~40dB S/N
- Longitudinal BTF – phase modulate RHIC RF?
- Relative device? How to calibrate?

Outline

- ERL portion of RHIC eCooler
- The Cooling Section
  - Machine Parameters
  - Devices and Accelerator Physics Requirements
- Diagnostics by system
  - BPMs
  - Velocity match
  - Recombination
  - Schottky/IPM
  - Beam Transfer Function
  - what else?

- **Conclusion**

Conclusion

- diagnostics for eCooling is pretty much unexplored territory for RHIC Diagnostics team – we have a lot to learn, seek to benefit from those who have actual experience
- We have a very preliminary plan that we think meets a good portion of the needs
- looking for advice regarding what needs to be measured
- looking for advice on how to better utilize existing RHIC diagnostics for eCooling
- looking for good ideas for new diagnostics

What else?

- antennas for CSR microwave instability
  - needed? where? what frequency?
- what else?

Back-up slides
(many are outdated)

ERL Machine Parameters – non-Magnetized Cooling

Parameter	Value	Diagnostic
injection energy [MeV]	4.7	
maximum beam energy [MeV]	54	spectrometer, Compton,…
rms bunch length [ps]	30	WCM, zero phasing, streak camera,…
RF frequency [MHz]	703.75	
bunching freq [MHz]	9.383	
bunch charge [nC]	5	
average beam current [mA]	50	DCCT
ε_x, ε_y at 4.7MeV [mm-mrad]		Pepper pot
ε_z at 4.7MeV [psec-KeV]		Compton plus streak camera
ε_x, ε_y at 54MeV [mm-mrad]	<5	Synchrotron light, WS
ε_z at 54MeV [psec-KeV]		Streak camera, WS w/ dispersion
rms dp/p	10^{-3}	
energy recovery [%]	99.95	Cavity power
current recovery [%]	99.9995	Differential current, loss monitors

ERL Diagnostics Devices and AP Specifications

Device	Qty	Range	Accuracy	Resolution	Comments
Position/Phase					
BPM (button)	25	1/2 pipe rad	100μ	1μ (av)/5μ	Dual plane
Phase	25	+/- 180 deg	+/- 2 deg	0.2 deg	BPMs w/ I/Q
HOM probes	6				Mini-CF antennas
BBU/Transfer Function	1				kicker, sample scope,...
Beam Energy	2		$2x10^{-3}$	10^{-3}	Spectrometer, Compton
Loss					
BLM (PMT)	20	1-1000 rem/h	30%	0.5 rem/h	20msec and 1sec
		10^{2}-10^{5} nA-sec		50 nA-sec	damage at ~10uA-sec
Current					
Current	25		5%	1%	BPM sum signal
Current	2		1%	0.1%	Bergoz PCTs
Differential	1	10^{2}-10^{5}nA-sec	$5*10^{-6}$	$2*10^{-6}$	2 toroids w/ null
Profile					
Crosses(flags,wires,…)	16				
Wire Scanner - profile	2	Full aperture	0.2σ		SEM mode
Wire Scanner - halo	2			10^{-6}	BLM mode
Synchrotron Light	3		0.2σ		At bend magnets
Energy Spread	-		10^{-4}	10^{-5}	Not day one

RHIC eCooling Parameters		
Parameter	**Value**	**Diagnostic**
Ion beam energy [GeV/A]	100	Dipole current and Magnet Transfer Function
initial rms dp/p	10^{-3}	Schottky, WCM
initial rms bunch length [ns]	1.2	WCM
RF frequency [MHz]	197.043	
bunching freq [MHz]	9.383	
bunch charge [nC]	15	WCM
average beam current [mA]	150	DCCT
initial rms ε_x, ε_y [mm-mrad]	2.5	IPM, Schottky, Luminescence
cooling section length [m]	60	
cooling section β_x, β_y [m]	>200	

Parameter Comparison

RHIC eCooling Parameters	
Ion beam energy [GeV/A]	100
initial rms dp/p	10^{-3}
initial rms bunch length [ps]	1200
RF frequency [MHz]	197.043
bunching freq [MHz]	9.383
bunch charge [nC]	15
average beam current [mA]	150
initial rms ε_x, ε_y [mm-mrad]	2.5

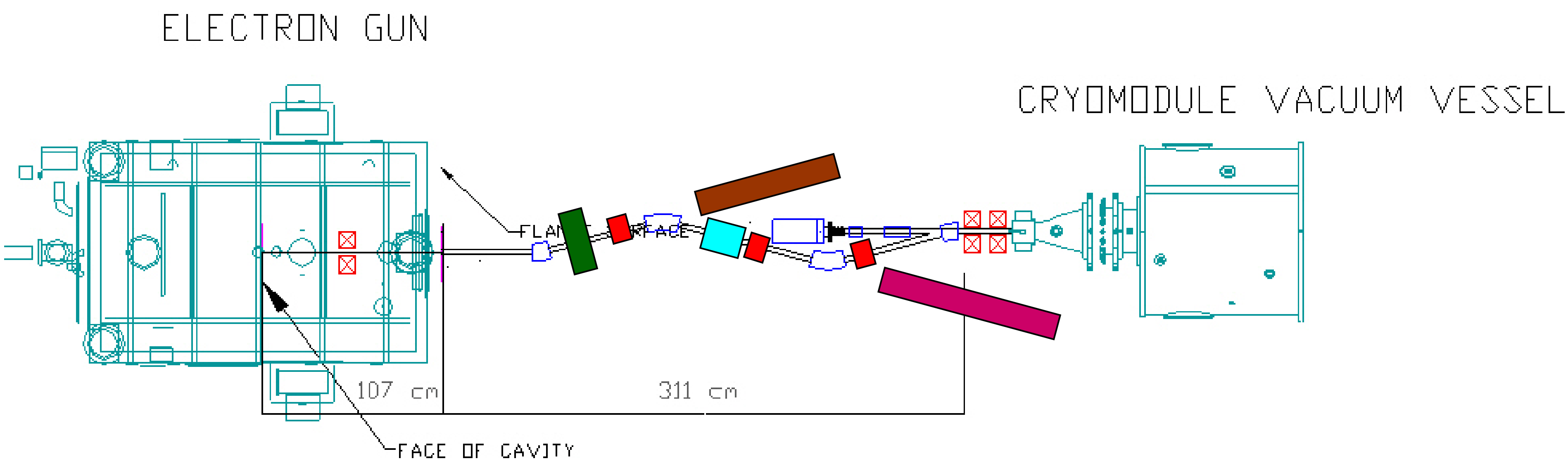
ERL Machine Parameters	
electron beam energy [GeV]	.054
rms dp/p	10^{-3}
rms bunch length [ps]	30
RF frequency [MHz]	703.75
bunching freq [MHz]	9.383
bunch charge [nC]	5
average beam current [mA]	50
rms ε_x, ε_y at 54MeV [mm-mrad]	<5

Outline

- The ERL
  - ERL Machine Parameters
  - Accelerator Physics Measurement Requirements - verify Machine Parameters
  - Diagnostics Layout - meet Measurement Requirements
  - Diagnostics by system
- The Cooling Section – non-Magnetized Cooling
  - RHIC/eCooling Machine Parameters
  - Accelerator Physics Measurement Requirements
  - Diagnostics by system
- **Diagnostics specific to Magnetized Cooling**
- Conclusion

ERL Injector Portion of RHIC eCooler

Legend:
- DCCT
- Button BPM
- Pepper pot
- BTF kicker
- Compton/Streak



Elevation View

e^- Beam Diagnostics – Loss

- AP current recovery spec is 99.9995%
  - at 50mA requires **~0.2μA accuracy**
- Damage threshold (loss pattern is important)
  - ~10 μA-sec at 54MeV
  - ~100 μA-sec at 4.7MeV
- Sensitivities at 54MeV:
  - PMT/scintillator BLMs ~.01 μA-sec (blind spots?)
  - Cable BLMs ~0.1 μA-sec (blind spots less an issue?)
  - Differential current DCCTs ~0.1 μA-sec or better?
- Sensitivities at 4.7MeV:
  - Loss monitors on the edge of being marginal?
  - Differential current particularly helpful here

e$^-$ Beam Diagnostics – Current

Current measurement

Bergoz 'new' PCT

resolution ~20μA with 40mA beam

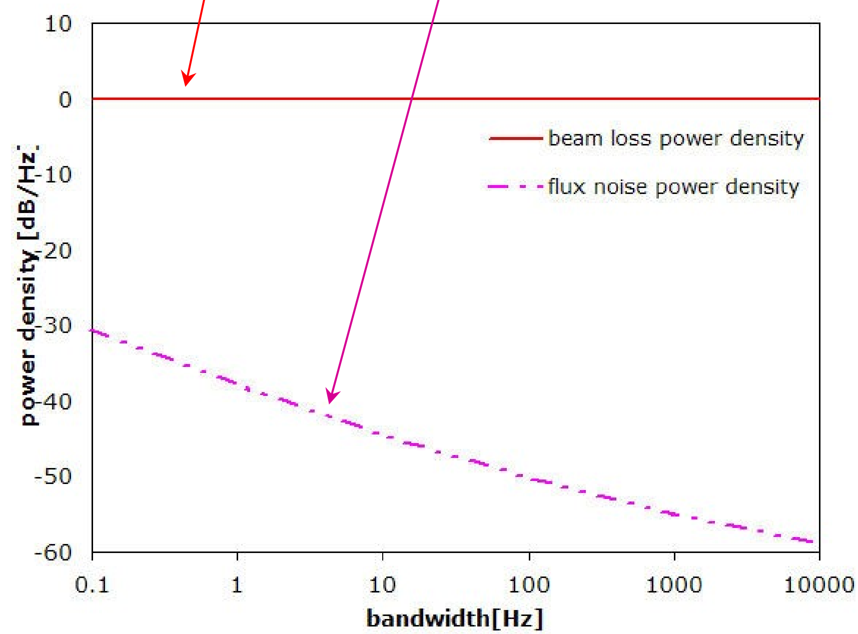
Differential Current

- PCTs linked by nulling winding, null beam current to gain dynamic range
- Frequent no-beam calibration for drifts
- Noise sources (uncorrected)
  - flux (Barkhausen) noise ~0.1mA/rtHz, 60dB above thermal
  - gain/linearity ~1ppm/mA
  - spurious field ~100mA/G
  - temperature ~5mA/K

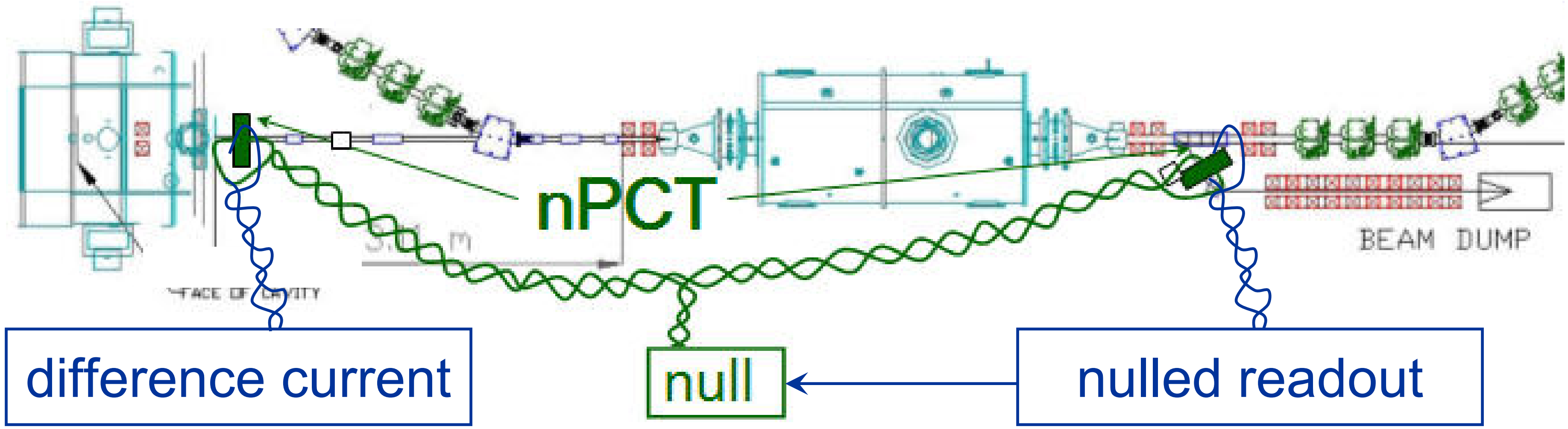
Removed by nulling

10 μA-sec loss

Barkhausen (flux noise) limit



Differential Current Measurement



utilizes nulling to attain ~ 10^{-6} resolution:

- DCCTs calibration windings are joined by a single loop, powered by a low-noise current source, driven opposite the beam
- Output of Dump DCCT is fed back to current source, to drive Dump DCCT output to zero
- Output of Gun DCCT is then the differential current measurement
- Drifts (thermal, gain, magnetic field) removed by nulling w/o beam

Proposal submitted in response to HEL-JTO BAA 05-DE-01

P. Cameron, "Differential Current Measurement in the BNL ERL", C-A AP Note 203

e^- Beam Diagnostics – Profile

- Wire Scanners - avoid proximity to SRF (cavity damage)
  - limited to <~10μA beam current for full profile
  - dynamic range ~ 10^6 or better gives good halo monitor
  - disadvantages - special mode, wire breakage, welded bellows,...
- Flags - again, avoid proximity to SRF if possible
  - dump line - for zero-phasing bunch length measurement?
- **Synchrotron Light**
- Streak Camera
- Differential Current
  - Halo control is crucial
  - high resolution, non-interceptive,...

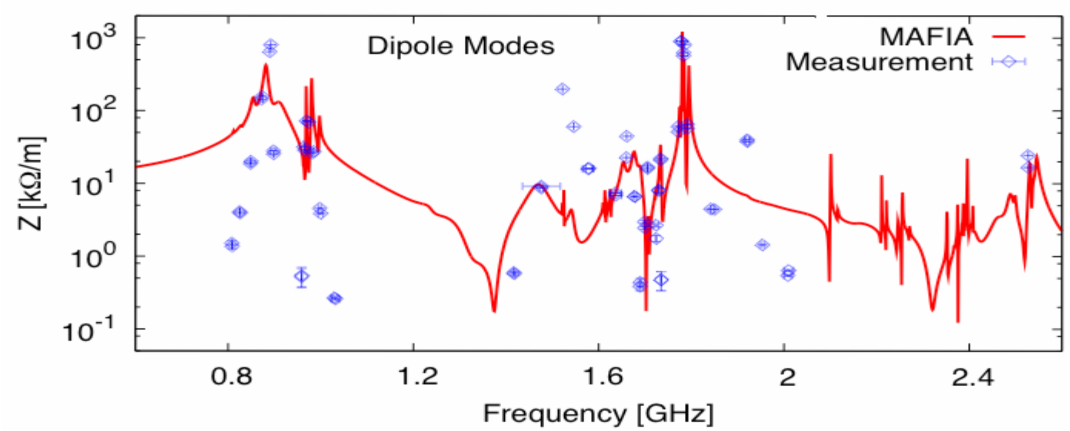
Beam Diags – HOM/BBU/BTF

HOM monitors

- 3 antennas in CF flange between cavity and absorber - both ends of SRF
- gate to eliminate direct pickup of bunch signal

Beam Transfer Function

- stripline kicker and pickup
  - null at ~1.3GHz
- excite, explore HOMs
- also excite with
  - longitudinal fill pattern?

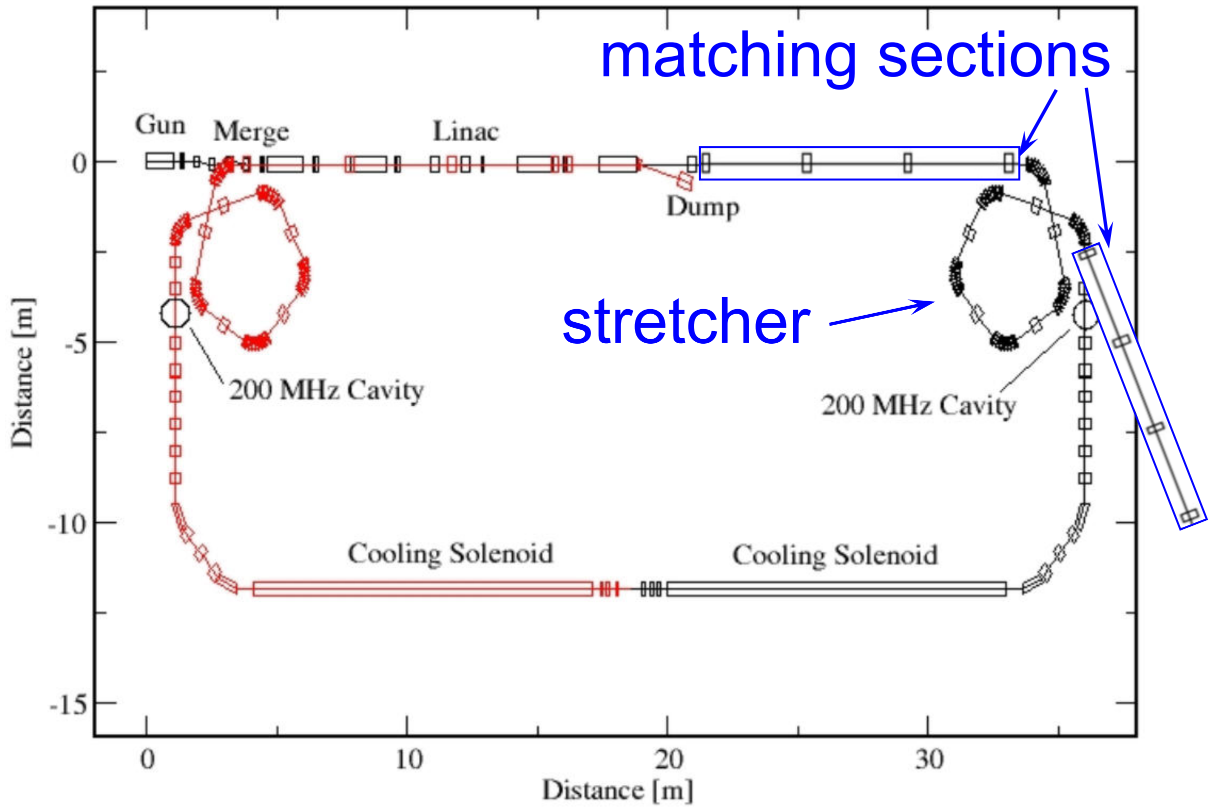


BBU monitors - timescale ~1msec

- BTF pickup with fast scope (also longitudinal profile monitor)
- Buttons with synthesized LO, BBU specific gate array code?
  - First filter is the problem

Magnetization Monitor

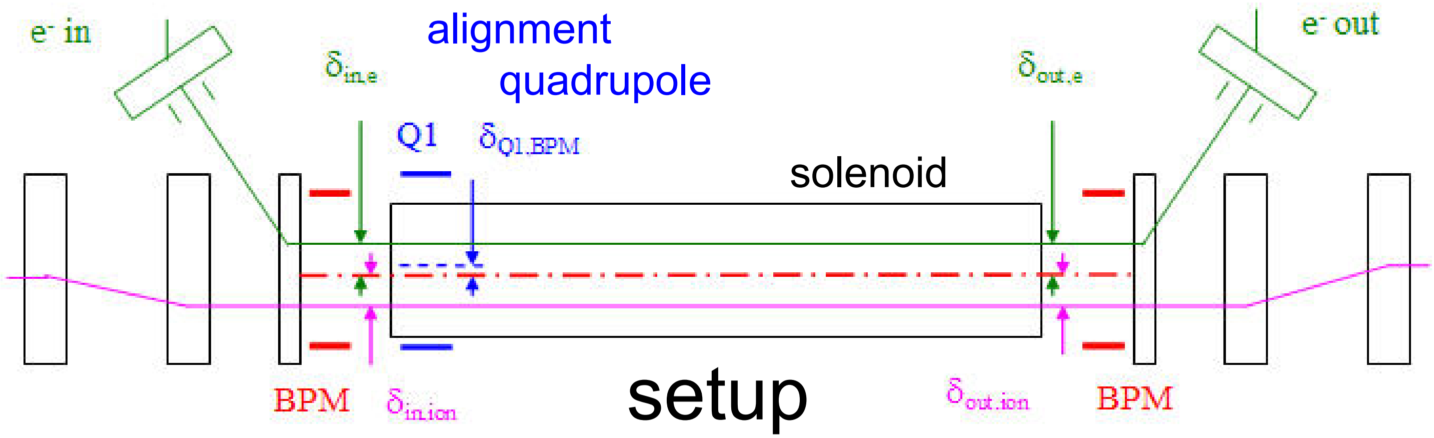
- Adjust betatron phase advances in matching section at end of linac to differ by 90 degrees in H and V - results in flat beam (**on flag**).
- From this extract the beam magnetization and the un-magnetized emittance.



- With diagnostic line/matching section downstream of the stretcher accomplish the same measurement
- This permits tuning of the dispersion and phase advance in the stretcher to minimize the contribution of longitudinal space charge to transverse emittance.

P. Cameron et al, "Beam Diagnostics for the RHIC eCooling Project", DIPAC 2005

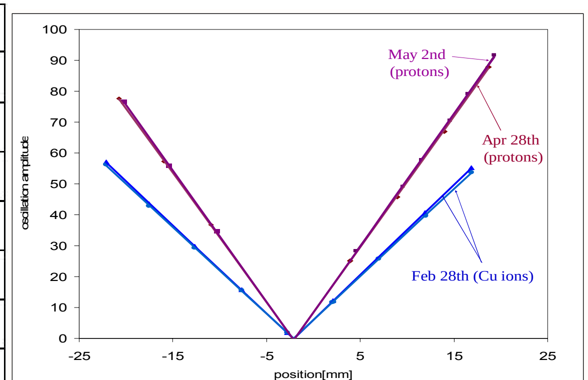
Beam-based Alignment



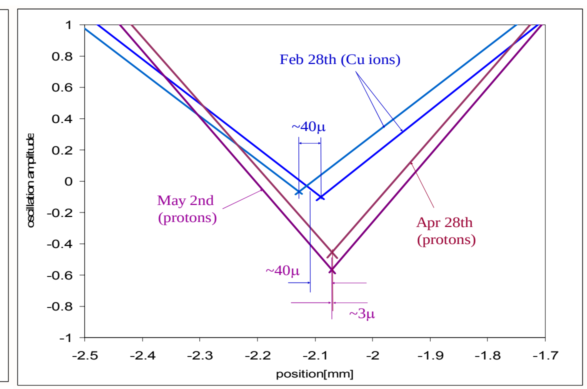
setup

measurement	accuracy	resolution	stability
$\delta_{Q1,BPM}$	7μ		
$\delta_{mod,ion}$	~125nm	~40nm	~40nm
$\delta_{in,ion}$ and $\delta_{out,ion}$	~3μ	~1μ	~1μ
$\delta_{Q1,e}$	7μ		
$\delta_{mod,e}$	~5μ	~2μ	~2μ
$\delta_{in,e}$	~3μ	~1μ	~1μ
$\delta_{\phi,e}$	~0.3μ	~0.1μ	~0.1μ

measurement requirements



beam expt



zoom

P. Cameron et al, "BBA in the RHIC eCooling Solenoids", PAC 2005

BROOKHAVEN NATIONAL LABORATORY

eCooling Workshop
26 May 06

RHIC